Hadronic centrality dependence in nuclear collisions

Sonja Kabana

Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland, e-mail: sonja.kabana@cern.ch

Abstract. The kaon number density in nucleus+nucleus and p+p reactions is investigated for the first time as a function of the initial energy density ϵ and is found to exhibit a discontinuity around ϵ=1.3 GeV/fm^3. This suggests a higher degree of chemical equilibrium for ϵ > 1.3 GeV/fm^3. It can also be interpreted as reflection of the same discontinuity, appearing in the chemical freeze out temperature (T) as a function of ϵ. The $N^{\alpha\sim 1}$ dependence of (u,d,s) hadrons, whith N the number of participating nucleons, also indicates a high degree of chemical equilibrium and T saturation, reached at ϵ >1.3 GeV/fm^3. Assuming that the intermediate mass region (IMR) dimuon enhancement seen by NA50 is due to open charm ($D\overline{D}$), the following observation can be made: a) Charm is not equilibrated. b) $J/\Psi/D\overline{D}$ suppression -unlike $J/\Psi/DY$- appears also in S+A collisions, above ϵ ∼1 GeV/fm^3. c) Both charm and strangeness show a discontinuity near the same ϵ. d) J/Ψ could be formed mainly through $c\overline{c}$ coalescence. e) The enhancement factors of hadrons with u,d,s,c quarks may be connected in a simple way to the mass gain of these particles if they are produced out of a quark gluon plasma (QGP). We discuss these results as possible evidence for the QCD phase transition occuring near ϵ ∼1.3 GeV/fm^3.

1. Introduction

The quark-gluon plasma phase transition predicted by QCD [1] may occur and manifest itself in ultrarelativistic nuclear collisions through discontinuities in the initial energy density (ϵ_i) dependence of relevant observables. A major example of a discontinuity is seen in the $J/\Psi/DY$ [2] discussed e.g. in [3, 4]. We investigate here for the first time the dependence of strangeness production, in particular of kaons, on the initial energy density ϵ_i. The degree of equilibrium achieved in nuclear collisions has been intensively studied comparing hadron ratios and densities to models (see e.g. [4, 5, 6, 7]). We investigate here if chemical equilibrium is achieved, examining an other aspect of equilibrium states, namely the volume (V) independence of hadron densities (ρ).

2. Results and discussion

The kaon density (ρ_K=(K per collision)/V) at the thermal freeze out in nuclear reactions, investigated as a function of the initial energy density ϵ_i (figure 1,(a)) (see [8] for calculation details), exhibits a dramatic changeover around ϵ=1.3 GeV/fm^3, saturating for higher ϵ values, while it is falling below. The syst. error on ϵ_i is estimated to be ∼ 30%. It is assumed that the number of nucleons participating in the collision (N) is proportional to the volume of the particle source at the thermal freeze out [8]. The new results from Si+Au at 14.6 A GeV and p+p at 158 A GeV shown in figure 1, which are not included in [8], have been estimated using data from [9] and methods described in [8]. Furthermore, ρ_K rises with N respectively with V below ϵ=1.3 GeV/fm^3 while it does not depend on N respectively on V above ϵ=1.3 GeV/fm^3. To illustrate this, two values of V are noted on figure 1. The changes of $K^{\pm}$ and $\pi^{\pm}$ with N within the Pb+Pb system, have been first realized in [10]. A

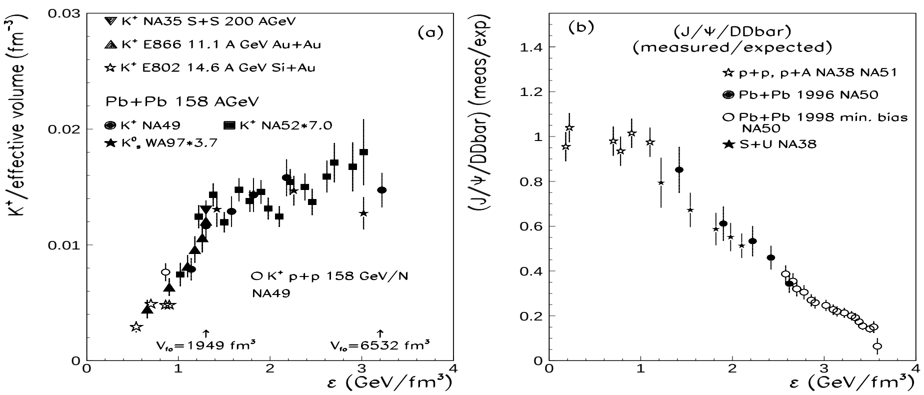

Figure 1. Initial energy density (ϵ) dependence of: (a) The K^+ multiplicity over the effective volume of the particle source at thermal freeze out. (b) The $J/\Psi/D\overline{D}$ (measured/'expected') ratio [8].

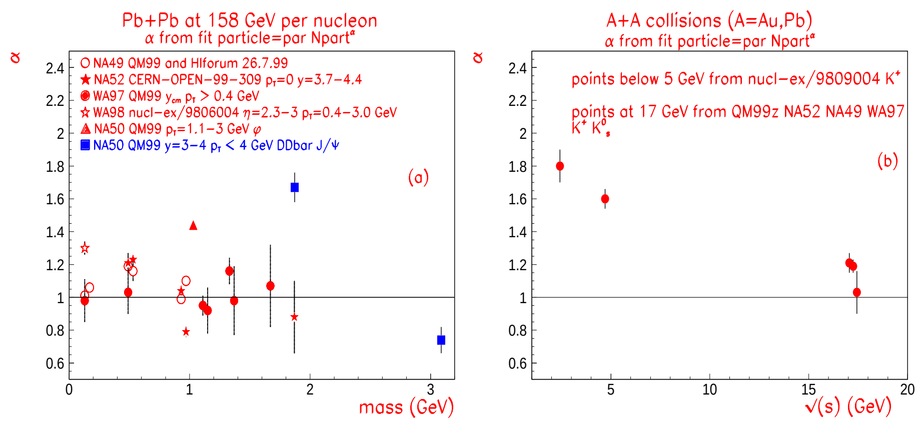

Figure 2. The parameter α, resulting from the N^α fit to hadron yields shown as a function of (a): the mass of the particles in the region ϵ >1.3GeV/fm^3 at SPS and (b) of the $\sqrt{s}$, for kaons. N is the number of participating nucleons.

similar behaviour as the one seen in figure 1, can be inferred for pions as well as for the K/π ratio (S.K. work in progress). The N^α exponent of hadrons with (u,d,s) quarks above ϵ=1.3 GeV/fm^3, do not depend on the particle mass (figure 2, (a)). At ϵ >1.3 GeV/fm^3 α is near to one, as expected in case of a chemically equilibrated state, assuming N $\sim$ V. The deviations seen in ϕ, π^0 and $\overline{p}$ may be due to the transverse momentum acceptance. Therefore, figure 2 (a) supports the assumption of a high degree of chemical equilibrium reached above ϵ=1.3 GeV/fm^3, among hadrons with u,d,s quarks. The N^α exponent of kaons is found to depend strongly on $\sqrt{s}$ for kaons (figure 2,(b)). Therefore, below ϵ=1.3 GeV/fm^3, ρ_k (figure 1 and figure 2 (b)), ρ_π and the K/π ratio, show an increase with increasing N respectively with V.

Figures 1 and 2 can be interpreted in two ways. Firstly, kaons may achieve a higher degree of chemical equilibrium only for ϵ > 1.3 GeV/fm^3, and may not be fully

equilibrated below [8]. The equilibration of strangeness is expected in a QGP and its observation at $\epsilon \sim 1.3$ GeV/fm^3 could therefore be a sign of a transition to QGP. In this case, it is a transition from a non equilibrated hadron gas to an equilibrated QGP. It is therefore not a well defined phase transition in the thermodynamic sense. Secondly, kaons can be in fact chemically equilibrated also below ϵ= 1.3 GeV/fm^3, and the change respectively the constancy of ρ_K with V_{fo} and ϵ_i observed in figure 1, can be a result of the increase of the freeze out temperature with ϵ_i below ϵ= 1.3 GeV/fm^3, respectively of the stability of T_{fo} above 1.3 GeV/fm^3. This dependence of T_{fo} on ϵ_i, namely rising until it reaches a critical T_c value and saturating above for all reactions, would strongly support the QCD phase transition appearing at $\epsilon \sim 1.3$ GeV/fm^3. This interpretation fully agrees with thermal models which suggest that particle ratios at freeze out are compatible with thermalization even in A+A collisions at 1 A GeV [5]. However the first interpretation is not in gross disagreement with [5], because there the thermal model description is modified (introducing e.g. $\rho_k \sim V$) in order to describe the data at 1 A GeV.
Furthermore, the correct interpretation can be corroborated by further investigations discussed in the following. The nonzero baryochemical potential (μ_B), which in the reactions shown in figure 1, happens to change with ϵ_i, makes the intepretation of figure 1 difficult. Therefore, it appears that the dependence of the temperature at chemical freeze out extrapolated to μ_b=0, on ϵ_i, would help to identify and prove the QCD phase transition. A rising and then a for ever saturating freeze out temperature above ϵ 1.3 GeV/fm^3 is a strong argument that the QCD phase transition occurs at this ϵ, and figure 1 is a direct consequence of it.
The question if the QCD phase transition appears at the critical ϵ_i in any volume, or if there is additionally a critical initial volume of the particle source above which the transition takes place, can be answered comparing QGP signatures in systems with different volumes but the same ϵ_i. For example comparing $p + p$, e^+e^- etc collisions to heavy ion collisions e.g. at the same ϵ. This is not yet done for the signature of the J/Ψ suppression and it has to be clarified e.g. using Tevatron data [8]. For the signature of strangeness enhancement it is suggested by figure 1 in [6] that there is indeed a critical initial volume, only above which strangeness is enhanced over $p + \overline{p}$ *at the same* ϵ_i. This conclusion follows, if we assume that Tevatron reaches at least ϵ_i values similar to SPS A+A collisions [11] and if figure 1 in [6] is not biased by the model calculation [6].
If strangeness is indeed not equilibrated at $\epsilon < 1.3$ GeV/fm^3, this may explain the decrease of the double ratio (K/π)(A+A/p+p) with increasing $\sqrt{s}$. In particular, a larger strangeness annihilation is enforced by equilibrium at SPS reducing the strange particle yield. However the assumption of non equilibrium of $s\overline{s}$ at low ϵ is not nessecary here, since the above observation can be possibly traced back to e.g. the variation of $\mu_B(A + A)/\mu_B(p + p)$ with $\sqrt{s}$ in A+A collisions. Furthermore, in the context of QGP formation, it seems irrelevant to discuss e.g. $s\overline{s}$ enhancement in A+B over p+p collisions in a nonequilibrium situation. It is the very establishment of equilibrium in the (u,d,s) sector, which can reveal informations on QGP.
The kaon number densities in p+p and A+B collisions in figure 1, (a) are similar, when compared at the same ϵ_i. See also [12] for a discussion of universality of pion phase space densities.
Our prediction for the N dependence of hadrons at RHIC and LHC is the N^1 thermal limit, as long as hadron yields are dominated by low transverse momentum particles. Furthermore, if the changeover of ρ_k at ϵ =1.3 GeV/fm^3 shown in figure 1 is due to

the QCD phase transition, we predict for RHIC and LHC the same total strangeness (or kaon) number density and the same freeze out temperature, -after correction for the μ_B dependence-, as for ϵ =1.3-3.0 GeV/fm^3. If this change is however due to the onset of equilibrium in a hadronic gas, and the QCD phase transition takes place at higher ϵ, it may manifest itself through a second changeover of hadron number densities, ratios and freeze out temperatures -after correction for the different μ_B- e.g. in RHIC above $\epsilon \sim 3$ GeV/fm^3.

Assuming that the IMR dimuon enhancement seen by NA50 is due to open charm, the following observations can be made: a) open charm appears not to be equilibrated (α = 1.7) (figure 2, (a)) [8]. b) The $J/\Psi/D\overline{D}$ ratio deviates from p+p and p+A data also in S+U collisions (figure 1, (b)), above ϵ ∼1 GeV/fm^3. c) It therefore appears that both charm and strangeness show a discontinuity near the same ϵ∼1 GeV/fm^3 [8], similar to the critical ϵ_c ∼1-2 GeV/fm^3 predicted by QCD [1, 3]. d) The N dependence of the $J/\Psi/D\overline{D}$ ratio can be interpreted as the J/Ψ being formed through $c, \overline{c}$ coalescence [8]. e) Finally, the enhancement factors of hadrons with u,d,s,c quarks may be connected in a simple way to the mass gain of these particles in the quark gluon plasma (table below) [13]. T_q are the enhancement factors of the lightest mesons with u,d,s,c quarks (π, K, D), if they are produced out of a quark gluon plasma (e.g. $g + g \rightarrow s + \overline{s}$ (1)), as compared to their direct production from hadron interactions away from the transition point (e.g. $p + p \rightarrow K^+ + \Lambda + p$ (2)). The gain is taken proportional to $m_{particle} - m_{quarks}$, as this expresses the different thresholds of reactions (1) and (2). In the table below the predicted enhancement factors (T_q) of hadrons with u,d,s,c quarks from a QGP are compared to the experimentally measured ones (E_q), and are found to be similar. (Definitions: $th_q = m_0 - m_q$, $m_{u,d}$=7 MeV, m_s=175 MeV, m_c=1.25 GeV, $m_0 = m(\pi, K, D)$).

Quark flavour	th_q	$T_q = \sqrt{th_q/th_{u,d}}$	$E\frac{(A+B}{(N+N)}$	$E_q = E/E_{u,d}$
u,d	133	1	$\pi/N \sim 1.12$	1
s	320	1.55	$K/N \sim 2$	1.79
c	615	2.15	$D\overline{D}$ meas/exp ~ 3	2.68

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